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Wall-Plug Efficiencies of FEL Amplifiers and Oscillators Employing Energy Recovery Linacs

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14. ABSTRACT

In a high average power FEL, the wall-plug efficiency is of critical importance in determining the size, complexity, and cost of the overall system. The wall-plug efficiency for the FEL oscillator and amplifier (uniform and tapered wiggler) are obtained and compared. In general, we find that the wall-plug efficiency for the tapered wiggler FEL amplifier is more than a factor of two greater than that of the oscillator. For typical MW class FEL parameters, we find that the wall-plug efficiency for the oscillator is in the range of 5-10%. The wall-plug efficiency for the uniform wiggler amplifier is found to be 5-10%, and for the tapered wiggler amplifier, the wall-plug efficiency is 20-25%.

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Abstract

In a high average power FEL the wall-plug efficiency is of critical importance in determining the size, complexity and cost of the overall system. The wall-plug efficiency for the FEL oscillator and amplifier (uniform and tapered wiggler) are obtained and compared. In general, we find that the wall-plug efficiency for the tapered wiggler FEL amplifier is more than a factor of two greater than that of the oscillator. For typical MW class FEL parameters, we find that the wall-plug efficiency for the oscillator is in the range $\eta_{WP} \approx 10-15\%$. For the uniform wiggler amplifier $\eta_{WP} \approx 10-15\%$, and for the tapered wiggler amplifier $\eta_{WP} \approx 20-25\%$.

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Introduction

The purpose of this paper is to calculate and compare the wall-plug efficiencies of high-power FEL amplifiers and oscillators employing energy recovery linacs (ERL). For MW class FELs, the wall-plug efficiency is of major importance in determining the size and cost of the system. The FEL wall-plug efficiency can be improved by use of ERLs [1]. An FEL based on an ERL is shown schematically in Fig. 1. In an ERL the injected electron beam is accelerated by RF fields and sent to the FEL interaction region. The spent electron beam from the FEL is sent back to the ERL and decelerated in the same RF field. The decelerated beam is then sent to a beam dump. In what follows, we define the wall-plug efficiency and calculate it for FEL oscillator, amplifier, and tapered amplifier configurations.

Wall-Plug Efficiency

In the steady state, the following energy balance relationship exists (Fig. 1)

$$\eta_{RF}\,(\,E_{wall-plug} - E_{misc}\,) = E_{FEL} + E_{dump} + E_{loss}\,, \tag{1}$$

where η_{RF} is the efficiency of generating the RF fields for the injector and ERL, $E_{wall-plug}$ is the wall-plug energy, E_{misc} is the energy for the cryogenics, magnets, etc., E_{FEL} is the optical FEL energy, E_{dump} is the electron beam energy entering the dump and E_{loss} is the total energy loss due to electron beam halos, synchrotron radiation, etc. The general expression for the wall-plug efficiency for either the FEL amplifier or oscillator is

$$\eta_{WP} = \frac{E_{FEL}}{E_{wall-plug}} = \frac{E_{FEL}}{(E_{FEL} + E_{dump} + E_{loss})/\eta_{RF} + E_{misc}}\,. \tag{2}$$

In general, the wall-plug efficiency can be far higher than the optical FEL efficiency, η_{FEL}, when an ERL is employed. Within the FEL interaction region the electron beam loses energy and develops an induced energy spread. In addition to the induced energy spread the beam has an initial intrinsic energy spread which is typically < 1 % of the beam energy and is neglected in the following considerations. The energy loss is $E_{loss} = \eta_{loss}\,E_b$ where η_{loss} is the loss efficiency and E_b is the electron beam energy entering the wiggler. There is a minimum energy, $E_{\min}$, that the electrons can be decelerated to in the ERL. This minimum energy is due to various effects such as excessive electron de-phasing in the RF field and transverse emittance blowup. In the following comparisons we take $E_b = 80\,\mathrm{MeV}$, $\eta_{RF} = 60\%$, $E_{\min} = 4\,\mathrm{MeV}$, $\eta_{loss} = 1\%$ and $E_{misc} = 1\,\mathrm{MeV}$.

Oscillator

Consider first an untapered FEL oscillator [2] and the associated wall-plug efficiency with an ERL [1,3]. The optical energy is $E_{FEL} = \eta_{FEL} E_b$ where the optical efficiency is $\eta_{FEL} = 1/(2N_w)$ and N_w is the number of wiggler periods. The electron beam energy exiting the decelerating RF fields within the ERL and entering the beam dump is

$$E_{dump} = E_{\min} + \delta E_{osc} / 2, \tag{3}$$

where δE_{osc} is the induced electron beam energy spread. In an FEL oscillator the energy spread is proportional to the optical energy, αE_{FEL}, where $\alpha > 1$. The electron beam energy spread entering the ERL can be reduced by a factor $\beta_{debunch} \leq 1$ and is

$$\delta E_{osc} = \beta_{debunch} \alpha \eta_{FEL} E_b . \tag{4}$$

The debunching parameter, $\beta_{debunch}$, accounts for the reduction in energy spread due to the spatial spreading of the beam outside of the wiggler. In all of the following examples we take $\beta_{debunch} = 1$. The wall-plug efficiency associated with the oscillator is

$$\eta_{WP} = \frac{\eta_{RF} \eta_{FEL}}{\eta_{FEL} (1 + \alpha/2) + E_{\min}/E_b + \eta_{loss} + \eta_{RF} E_{misc}/E_b} . \tag{5}$$

Example: As an illustration, we take $N_W = 25$, $\alpha = 4$ and find that the optical FEL oscillator efficiency is $\eta_{FEL} = 2\%$ and the wall-plug efficiency is $\eta_{WP} = 10\%$.

High-Gain Amplifier

In a high-gain uniform wiggler amplifier the radiation can be optically guided if the electron current is sufficiently high [4]. In addition, pulse slippage is significantly reduced compared to the low gain regime [4]. In a tapered wiggler amplifier, optical guiding can also be achieved even in the trapped particle regime.

a) Uniform wiggler

The wall-plug efficiency associated with the high-gain untapered wiggler amplifier is

$$\eta_{WP} = \frac{\eta_{RF} \eta_{FEL} E_b}{\eta_{FEL} E_b + E_{dump} + \eta_{loss} E_b + \eta_{RF} E_{misc}} , \tag{6}$$

where the electron beam energy entering dump is $E_{dump} = E_{\min} + \delta E_{amp}/2$. The induced energy spread is approximately equal to the optical energy, i.e., $\delta E_{amp} = \beta_{debunch}\,\eta_{FEL}\,E_b$. The wall-plug efficiency for the untapered amplifier becomes

$$\eta_{WP} = \frac{\eta_{RF}\,\eta_{FEL}}{(1+\beta_{debunch}/2)\eta_{FEL} + E_{\min}/E_b + \eta_{loss} + \eta_{RF}\,E_{misc}/E_b}. \tag{7}$$

The optical efficiency, η_{FEL}, in a uniform wiggler amplifier can be increased by approximately a factor of 2 by frequency detuning [4].

Example: As an illustration, we take $\eta_{FEL} = 1.5\%$ [4], and find that the wall-plug efficiency is $\eta_{WP} = 10\%$.

b) Tapered Wiggler

In a high-gain tapered wiggler amplifier the optical output energy is [4, 5]

$$E_{FEL} = \eta_{FEL}\,E_b = \eta_{trap}\,\Delta E_b, \tag{8}$$

where $\eta_{FEL} = \eta_{trap}\,\Delta E_b / E_b$ is the optical efficiency, η_{trap} is the trapping efficiency, i.e., fraction of electrons trapped in the ponderomotive bucket, and ΔE_b is the change in the electron beam energy associated with the trapped electrons. Figure 2 shows a sketch of the electron energy distribution in a tapered wiggler amplifier. The electron beam energy entering the beam dump is

$$\begin{aligned} E_{dump} &= \eta_{trap}\left(E_{\min} + \delta E_{amp}/2\right) + (1-\eta_{trap})\left(\Delta E_b + E_{\min} + \delta E_{amp}/2\right) \\ &= (1-\eta_{trap})\Delta E_b + E_{\min} + \delta E_{amp}/2 \end{aligned}, \tag{9}$$

where δE_{amp} is the induced full energy spread associated with the trapped electrons in the ponderomotive bucket. The wall-plug efficiency associated with the high-gain tapered wiggler FEL amplifier becomes

$$\eta_{WP} = \frac{\eta_{RF}\,\eta_{trap}\,\eta_{FEL}}{\eta_{FEL} + \eta_{trap}\left(E_{\min}/E_b + \delta E_{amp}/2E_b + \eta_{loss} + \eta_{RF}\,E_{misc}/E_b\right)}. \tag{10}$$

The energy spread associated with the trapped electrons is

$$\delta E_{amp} \approx \beta_{debunch}\left(\frac{K}{1+K^2/2}\right)^{1/2} a_R^{1/2}\left(E_b - \Delta E_b\right), \tag{11}$$

where $a_R = 6\times10^{-10}\,\lambda[\mu\mathrm{m}]\,I^{1/2}[\mathrm{W/cm^2}]$ is the normalized vector potential associated with the optical field of wavelength λ, and K is the wiggler strength parameter. For a megawatt class average power FEL, the peak optical intensity within the wiggler is $I = 2P/(\pi R_L^2) \approx 10^{10}$ W/cm^2 ($a_R \sim 10^{-4}$), R_L is the laser spot size, and the fractional trapped electron energy spread is $\delta E_{amp}/E_b \approx 10^{-2}$.

Example: As an illustration, we take $\eta_{trap} = 50\%$, $\Delta E_b = 0.2\,E_b$, $\delta E_{amp}/E_b \approx 10^{-2}$. For these parameters the intrinsic FEL optical efficiency is $\eta_{FEL} = 10\%$ and the wall-plug efficiency is $\eta_{WP} = 22\%$.

Conclusions

We have calculated the wall-plug efficiency for an FEL oscillator, amplifier, and tapered amplifier configuration employing an energy recovery linac. The wall-plug efficiency depends on various FEL-ERL parameters and can be improved, for example, by reducing the minimum energy entering the beam dump, $E_{\min}$. By reducing $E_{\min}$ from 4 MeV to 2 MeV and keeping all other parameters the same the wall-plug efficiency for the oscillator increases from 10% to 12%; for the uniform wiggler amplifier the efficiency increases from 10% to 14%; and for the tapered wiggler amplifier the efficiency increases from 22% to 24%. For typical MW class FEL parameters, we find that the wall-plug efficiency for the oscillator is in the range $\eta_{WP} \approx 10-15\%$. For the uniform wiggler amplifier $\eta_{WP} \approx 10-15\%$, and for the tapered wiggler amplifier $\eta_{WP} \approx 20-25\%$.

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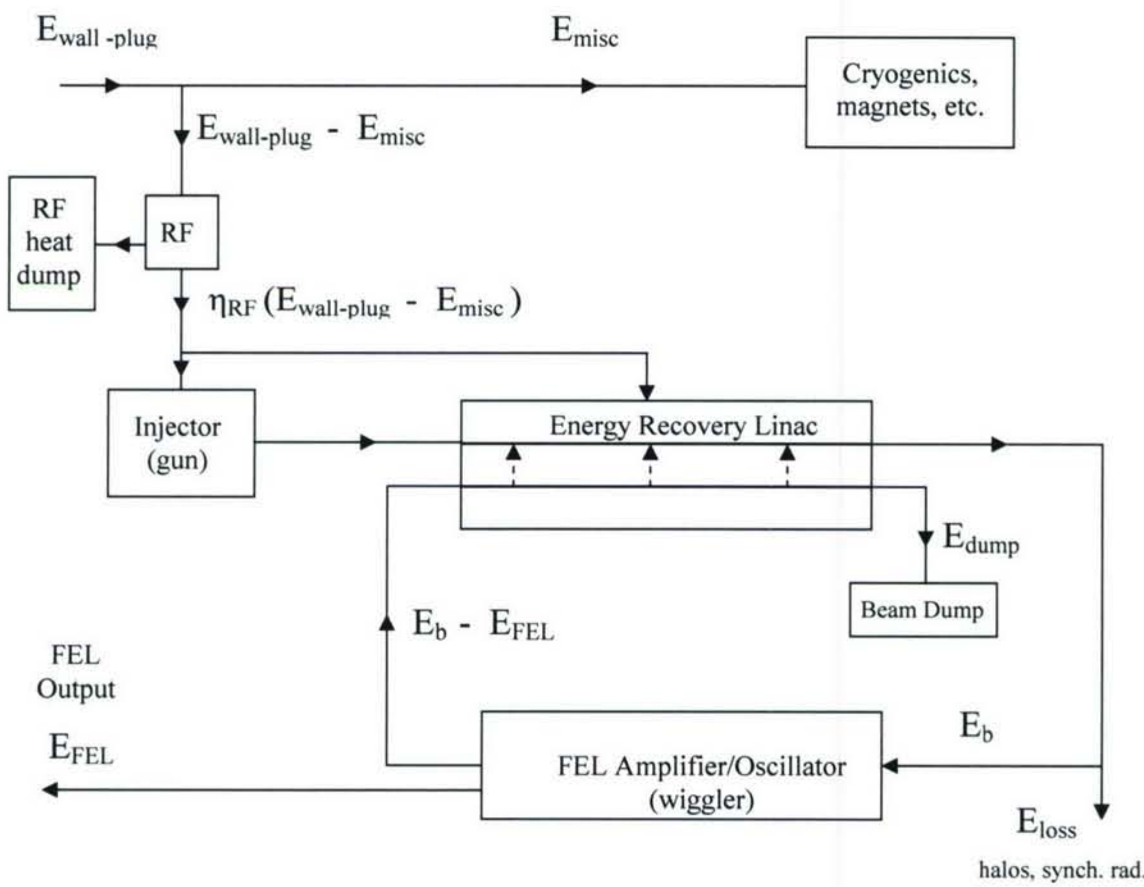

Figure 1: Energy flow diagram of an FEL employing an ERL which is used to derive the wall-plug efficiency.

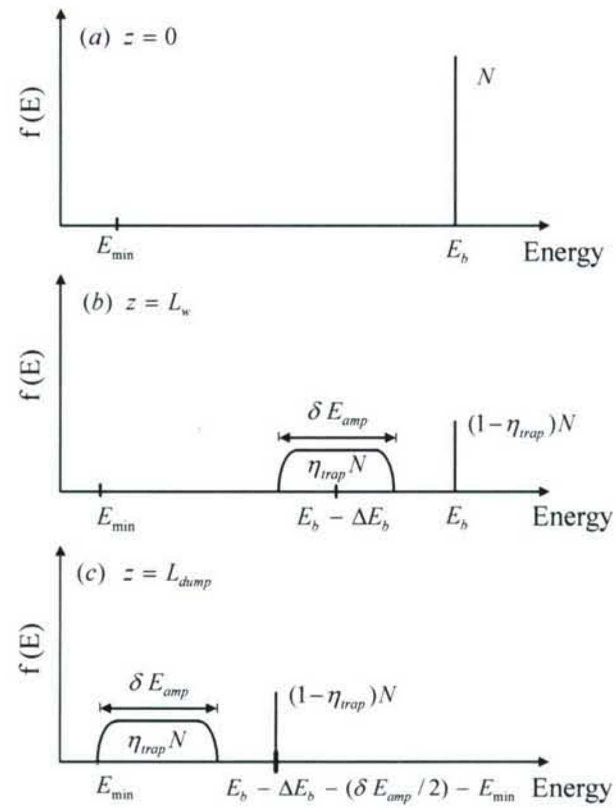

Figure 2: Illustration of the electron energy distribution used to obtain Eq. (9). Figure (a) shows the electron distribution function at the wiggler entrance ($z = 0$), a beam of N electrons with energy E_b. Figure (b) shows the electron distribution at the tapered wiggler exit ($z = L_w$). A fraction of electrons η_{trap} are trapped and de-accelerated to an average energy $E_b - \Delta E_b$. The trapped particles have an induced energy spread δE_{amp}. Figure (c) shows the electron distribution at the beam dump. Both trapped and un-trapped electrons are de-accelerated by an amount $E_b - \Delta E_b - (\delta E_{amp}/2) - E_{min}$. The total energy entering the beam dump in Fig. (c) is given by Eq. (9).